Assessment of Environmental Impacts of Conflict-Reducing Traffic Control Strategies on the Arterial Streets

Slavica Gavric[1], Nikola Mitrovic[2], Aleksandar Stevanovic*[3]

[1] Graduate Student Researcher, Department of Civil and Environmental Engineering, University of Pittsburgh, USA

[2] Lead Transportation Research Scientist, BlueHalo, USA

[3] Associate Professor, Department of Civil and Environmental Engineering, University of Pittsburgh, USA

SHORT SUMMARY

Historically, flexible lane management has been underutilized in mitigating traffic congestion, despite its potential to increase traffic flow capacity. Recent studies have explored strategies integrating flexible lane management and reservation-based traffic control to enhance safety and efficiency. However, these studies neglected to evaluate the environmental aspect of such lane management. This paper conducts an environmental assessment of strategies that reduce conflicts at intersections. A representative conflict-reducing traffic control scheme is evaluated using the Comprehensive Modal Emission Model (CMEM) and is compared to conventional fixed-time signal control and Fully Reservation-based Intersection Control (FRIC). The results indicate that schemes that move conflicts away from the intersection and distribute them along the link: (a) surpass other control methods in fuel consumption reduction, and (b) lead to decreased emission scenarios at the network level compared to FT and FRIC. These findings underscore the potential environmental benefits of adopting conflict-reducing strategies on urban arterials.
Keywords: connected automated vehicles, traffic control, fuel consumption, emissions, CMEM

1. INTRODUCTION

Driving in congested urban traffic, marked by sudden speed changes and frequent stops at intersections, is linked to the highest fuel consumption on arterial roads. However, neither sparse traffic nor continuous flow ensures the lowest fuel consumption and emissions. Even on roads with low traffic demand, excessive speeding can lead to elevated emissions across various pollutants. Optimal traffic flow on arterial streets, concerning fuel consumption and emissions, occurs with minimal stops, brief delays, and moderate speeds consistently maintained during a commute (Stevanovic et al., 2009).
Most of the conventional traffic control strategies, which have shown some effectiveness in addressing traffic congestion issues, have almost exclusively focused on resolving the issues of traffic capacity on arterial streets at the traffic intersections. For this reason, researchers have been primarily focusing on improving traffic performance of signalized intersections via various traffic control algorithms. For instance, a concept named Autonomous Intersection Management (AIM) (Dresner and Stone, 2008) has been recognized as one of the first to improve intersection capacities by utilizing a novel approach of reserving times for passing through intersection, for individual vehicles. Many similar approaches have branched out this research in various directions where almost each new approach adds complexity and improves efficiency of the basic reservation-based intersection control (RIC) (Hausknecht et al., 2011a; Levin et al., 2017).

In meanwhile, some of the researchers have investigated movement of the live species in nature as an inspiration to improve mobility of the humans and vehicles in urban environment (Kato et al., 2002; Tian et al., 2015). Such studies introduce algorithms that try to mimic wild-animal-flocking through, where connected vehicles can move in a cooperative manner like fish and birds. Research of this type has been largely facilitated by recent rapid development of connected and autonomous vehicle (CAV) technologies, which have opened some opportunities to utilize the existing roadway infrastructure in a more flexible way than ever before. More specifically, CAV collaborative features can enable feasibility of flexible lane assignment concept, in which lanes are not necessarily grouped in the conventional directional way. It seems that removing limitations of the conventional lane assignment opens an opportunity to better organize directional arrivals of vehicles at downstream intersection, which can improve capacities of such intersections (Stevanovic and Mitrovic, 2018, 2019; Mitrovic et al., 2020; Azadi et al., 2022).
While previous studies investigated operational benefits of conflict-reducing strategies, environmental aspect of such strategies has not been investigated. Thus, this paper conducts an environmental assessment of conflict-reducing traffic control scheme. As a representative, flexible lane assignment scheme CADLARIC developed by (Mitrovic et al., 2020) is utilized. After, such flexible lane assignment scheme is evaluated using the CMEM and is compared to conventional fixed-time signal control and FRIC.
The remaining of the paper is structured as follows. First, we present the overview of our methodology. After that, the results are provided and accompanied by a brief discussion. Finally, the concluding remarks are presented with future research possibilities.

2. METHODOLOGY

The methodology is organized as follows: First, we provide an explanation of the background of the representative conflict-reducing traffic control along with its main assumptions and explanations. Following that, we describe the developed microsimulation platform. Additionally, we explain the emissions model used and the test network. Finally, the experimental setup is detailed.

Representative conflict-reducing traffic control

In the conventional FTC system employing a standard lane assignment, which is the least flexible control system, all conflicts between vehicles are managed through traffic signals within the intersection box. There are no intersection-based conflicts among vehicles moving in the same direction (Urbanik et al., 2015). Introducing a reservation-based system (Dresner and Stone, 2008) enhances flexibility by incorporating an "intersection manager" that resolves conflicts through a reservation process for traditional lane assignment structures. To further enhance flexibility, various lane assignment schemas can be integrated into RIC.

The control concept presented by Stevanovic and Mitrovic, known as Combined Alternate-Direction Lane Assignment and Reservation-Based Intersection Control (CADLARIC), aims to decrease intersection conflict points but introduces the challenge of resolving conflicts at the link (Stevanovic and Mitrovic, 2018). Broadly speaking, rather than relying on a reservation-based system to handle all conflicts at the intersection, the suggested CADLARIC control scheme allocates different turning flows to distinct lanes in an alternating manner, as illustrated in Figure 1. This approach ensures that left and right movements traverse the intersection without conflicts, narrowing potential issues to those between vehicles engaged in through intersection movements. Subsequently, a Reservation-based Intersection Control (RIC) system, akin to the one outlined in (Dresner and Stone, 2008) is implemented to manage conflict avoidance at the intersection itself.

When a specific vehicle, denoted as i, approaches an intersection at time t, it is necessary to reserve a subset of cells (space blocks), represented by $D_i(t) \in D$, where potential conflicts with other vehicles may arise (Figure 1). This reservation is essential for the safe traversal of the intersection area. It is important to note that only vehicles meeting the following three conditions are eligible to reserve the associated cells within the intersection area at a given time. Firstly, the vehicle must be within maximum communication range distance. Secondly, it must be traveling in the designated lane for its intended movement. Thirdly, its leading vehicle must have already reserved the corresponding cells. In the case that all requested cells can be reserved for a specific vehicle i, the path is assigned to that particular vehicle. Detailed algorithms for time-space reservation and lane changing are given in authors previous work (Mitrovic et al., 2020).

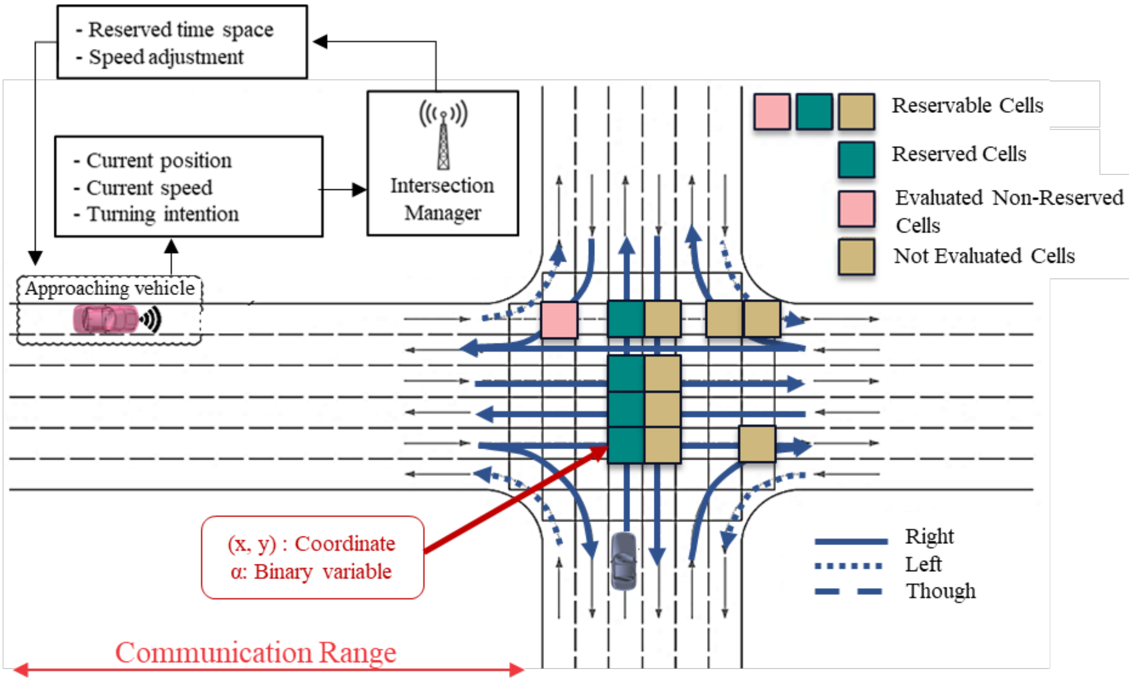

Figure 1: Time-Space Reservation and lane assignment in CADLARIC

Conflict resolution

While conflict resolution in fixed-time and fully reservation-based concepts mostly occurs at intersections, certain flexible lane assignment concepts (Hausknecht et al., 2011b; Gravelle and Martínez, 2018; Stevanovic and Mitrovic, 2018; Mitrovic et al., 2020; Azadi et al., 2022, 2024) shift conflicts away from the intersection and distribute them along the links between intersections. In these cases, the number of lane-changing conflicts increases, while the number of crossing conflicts significantly decreases (Figure 2). The primary objective of this approach is to minimize the number of stops for vehicles, enabling them to navigate intersections more smoothly. Moreover, all right and left turning conflicts are eliminated and only through conflicts exist in the intersection eliminating conflict points to only four (Mitrovic et al., 2020).

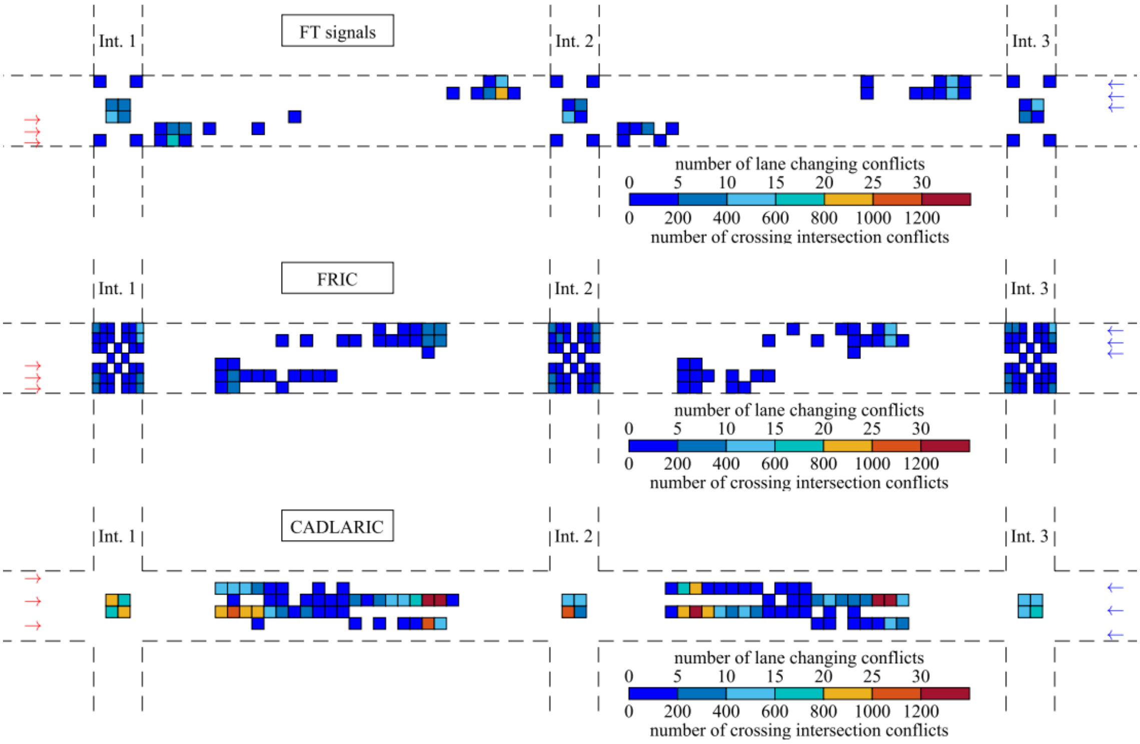

Figure 2: Spatial distribution of conflicts in case of: FT signal control; FRIC; and CADLARIC

Microsimulation platform

The limitations in implementing innovative traffic management methods are not solely confined to field conditions. While numerous simulation tools can realistically simulate conventional traffic operations (e.g., Vissim, Aimsun), many of them struggle to accurately simulate the flexible bi-directional utilization of the entire road pavement.(Stevanovic and Mitrovic, 2019). As an illustration, these tools operate as though there is consistently an imaginary median between lanes in opposing directions, an aspect that proves unnecessary in a futuristic CAV transportation environment. Consequently, to model the suggested concept, wherein every vehicle in the network can freely utilize any section of the road surface irrespective of its direction, speed, and position, a microsimulation tool named FAUSIM is employed (Stevanovic and Mitrovic, 2019), through a series of custom-made codes written in NetLogo, an agent-based modeling platform (Uri Wilensky, 1999). The entire network, in the NetLogo platform, is discretized into cells where each cell is 0.7 m × 0.7 m. To address the issues linked with cell-based models and to implement advanced car-following models, the discrete space within NetLogo is transformed into a continuous one. This involves adjusting certain parameters of the vehicle, such as speed and position, to non-integer values. (Stevanovic and Mitrovic, 2019). In FAUSIM, time intervals are discrete, and each simulation step is 0.2 s. Detailed descriptions of the algorithms and modules within FAUSIM are given in the authors' previous studies (Stevanovic and Mitrovic, 2019).
The proper validation of any newly developed microsimulation platform is imperative before it can be applied to test diverse traffic scenarios. To fulfill this requirement, the test network has been modeled in both Vissim (PTV Vissim 2022 User Manual, 2021) and FAUSIM with fixed-time signals with identical vehicular inputs, turning proportions, lane assignments, and signal timing parameters. The comparison results of the recorded travel times in FAUSIM and Vissim have been presented in the authors' previous study (Mitrovic et al., 2020).

Emission Model

While previous studies have explored flexible lane assignments focusing on efficiency and safety, this study takes a conventional approach by evaluating fuel consumption and emissions through the Comprehensive Modal Emission Model (CMEM). It assesses the emissions and fuel consumption generated by such a scheme. Essentially, we aim to determine whether a conflict-reducing scheme yields any environmental benefits.

CMEM (An et al., 1997) serves as a power-demand emissions model, providing estimates of fuel consumption and emissions (HC, CO, NOx, and CO2) on a second-by-second basis, based on vehicular speed and acceleration traces. The model's development involved over 300 tested vehicles. To utilize CMEM, a second-by-second speed trace is required, and these inputs can be obtained from FAUSIM.

The selection of CMEM for this study is justified by two reasons: 1 - Its capability to estimate emissions for various vehicle types and 2 - Its calibration and validation using data from the National Cooperative Highway Research Program (An et al., 1997). Additionally, previous studies have validated CMEM's estimates, confirming it as a widely accepted model capable of generating verifiable emissions estimates (Barth et al., 2000; Rakha and Ding, 2003).

Test network

This study evaluates the fuel consumption and emissions of conflict-reducing traffic concept (e.g., CADLARIC) to investigate whether moving conflicts away from the intersection reduces environmental impacts. All experiments are performed on a generic three-intersection network similar to the network used previously by (Stevanovic and Mitrovic, 2018). As is observable from Figure 3, the arterial has six lanes in each approach, which can be arranged as three lanes in each direction, if a conventional traffic management method is utilized. Origins and destinations of this arterial network are represented by encircled numbers next to each network entrance/exit in Figure 3; which also shows all of the turning proportions of the main (east-west) and side (north-south) streets.

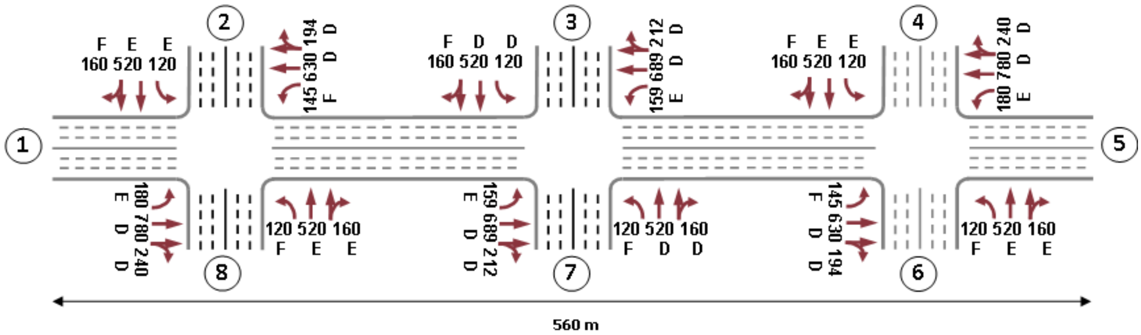

Figure 3: Schematic representation of the test network for LOS “D”

Experimental setup

Performances of the CADLARIC scenario is evaluated in comparison with the two base-case scenarios: FTC and FRIC. The lanes in FTC and FRIC are assigned conventionally, with three lanes in each direction from which the most-right lane (in each direction) is shared between through and right-turning movements. However, CADLARIC (as shown in Figure 1) assigns various turning flows to different lanes in an alternate fashion, in such a way that left and right traffic movements go through an intersection without any conflicts, and potential conflicts are reduced only to those between through vehicles. The signal timings of the FTC scenarios were optimized, for the given traffic demands/LOSs, by VISTRO (PTV Vistro 2022 User Manual, 2021). Each of these scenarios was tested under five traffic demands representing LOS B, C, D, E, and F (Table 1) and five different random seeds.

Table 1: Traffic demand and distribution for the analyzed LOS scenarios

Traffic demand [vph]			Traffic distribution		
LOS	Major road	Minor road	Movement	Percentage	
				Major Road	Minor Road
B	300	200	Right	15	20
			Through	70	60
			Left	15	20
C	800	540	Right	15	20
			Through	70	60
			Left	15	20
D	1200	800	Right	15	20
			Through	70	60
			Left	15	20
E	1300	850	Right	15	20
			Through	70	60
			Left	15	20
F	1400	940	Right	15	20
			Through	70	60
			Left	15	20

3. RESULTS AND DISCUSSION

In Figure 4, emission results are depicted. It is evident that all emissions, except NOx, are reduced in CADLARIC for all levels of service except LOS F. The absence of shared lanes, which could potentially provide additional 'capacity,' seems to influence the emission outcomes for CADLARIC in LOS F. Notably, CADLARIC significantly reduces CO_2 for all other levels of service. The increase in emissions in LOS F appears to be attributed to the fact that each lane corresponds to specific movements, and no movements share a lane. This reduction in capacity in CADLARIC results in unnecessary queues, a challenge overcome by (Azadi et al., 2024) through the introduction of shared lanes for certain movements.

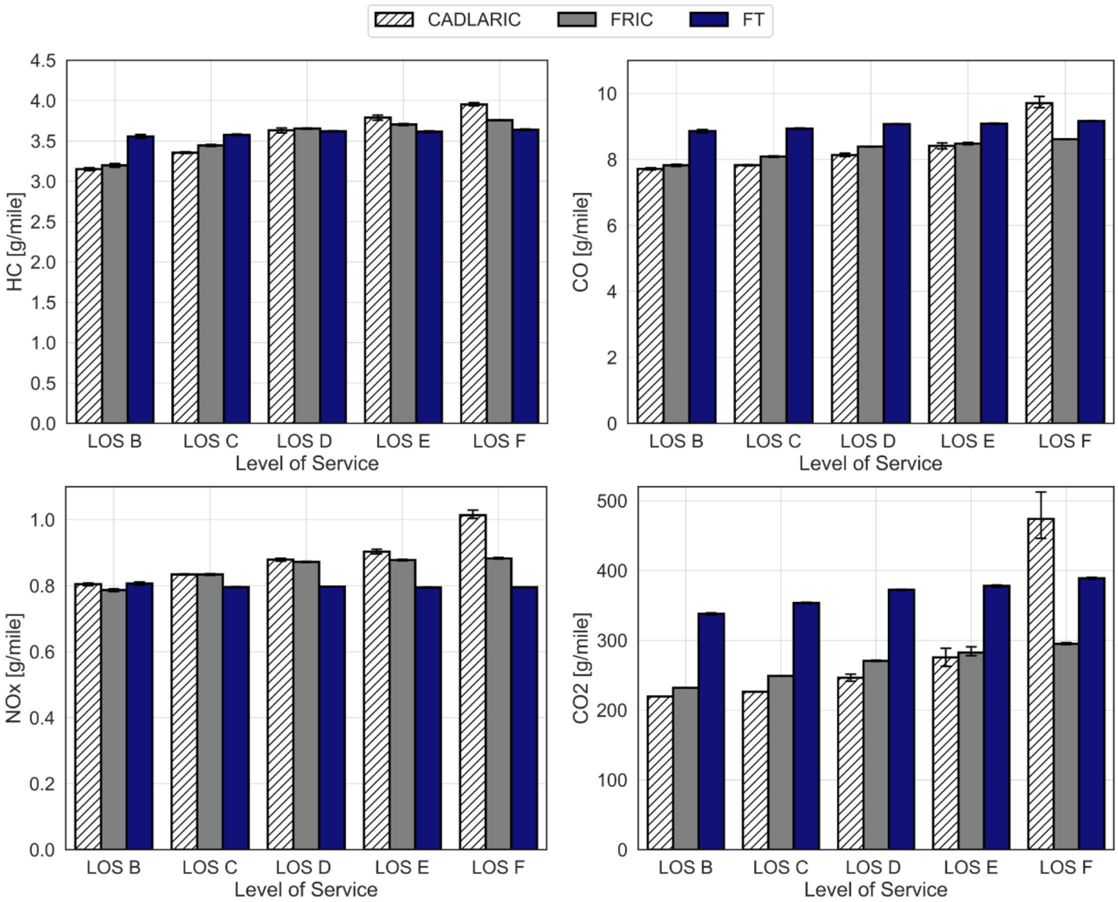

Figure 4: Emissions results

In Figure 5, fuel consumption results are presented. The increase in fuel consumption for LOS F is attributed to the utilization of exclusive lanes for all movements. In cases where lanes are shared, a lower number of vehicles would need to come to a complete stop (Azadi et al., 2024). Some authors (Rakha and Ding, 2003) found that an increase in stops and delays results in elevated fuel consumption and emissions. Thus, the authors speculate that shared lanes (Azadi et al., 2024) would reduce fuel consumption as well due to lower number of stops.

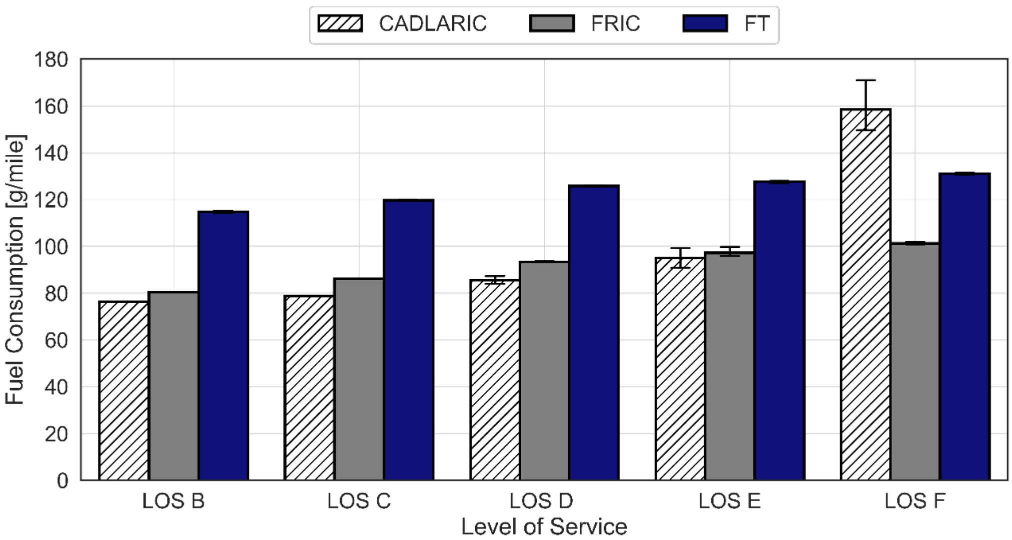

Figure 5: Fuel consumption results

4. CONCLUSIONS

In this paper, we evaluated the environmental impacts of conflict-reducing traffic control schemes. By comparing five control scenarios of a representative conflict-reducing scheme (i.e., CADLARIC) for different levels of service with fully reservation-based traffic control and fixed-time traffic control, we assessed the impact of CADLARIC on HC, CO, CO2, NOx, and fuel consumption. Our analysis suggests that moving conflicts away from intersections reduces emissions (except NOx) and fuel consumption for almost all levels of service, except LOS F. It appears that the network capacity was insufficient for LOS F, and this issue could potentially be addressed by introducing shared lanes for right and through movements. Future research should focus on optimizing lane assignments for fuel consumption and emissions, as conflict-reducing schemes seem to hold great potential for a connected and automated future.

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